Jet Propulsion Laboratory
California Institute of Technology

Origami wrapping patterns for non-planar unfolded forms

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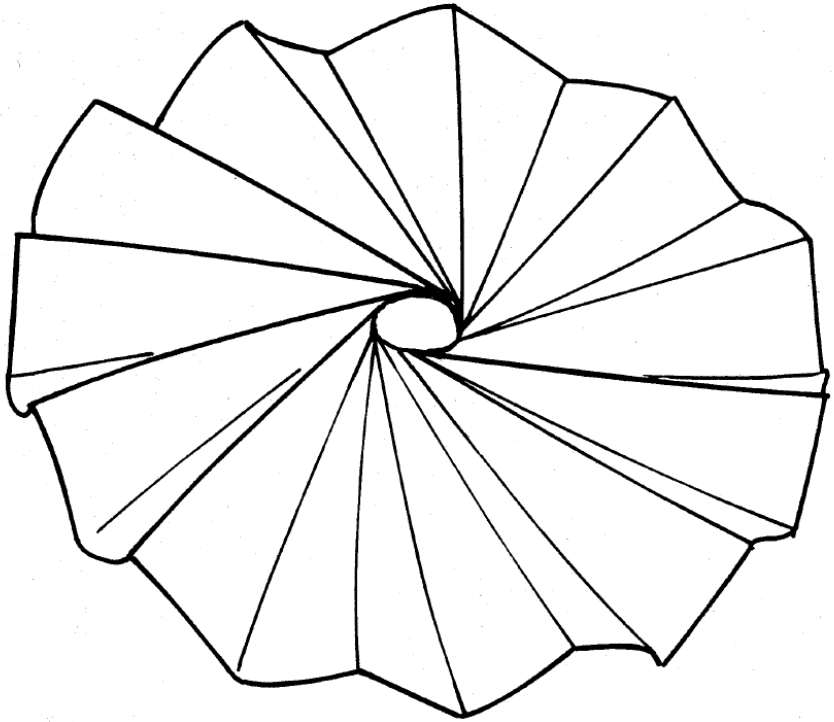
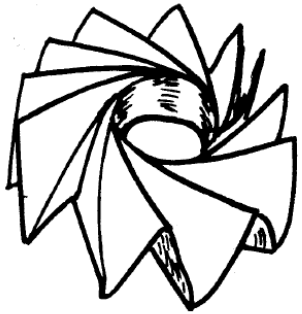
What is an origami wrapping pattern?

- Wraps sheet-like materials around a central body
- Generally, exhibits N-fold rotational symmetry





from S. D. Guest and S. Pellegrino, “Inextensional wrapping of flat membranes,”
in *First International Seminar on Structural Morphology*, September 1992, pp. 203–215.

Origami wrapping patterns

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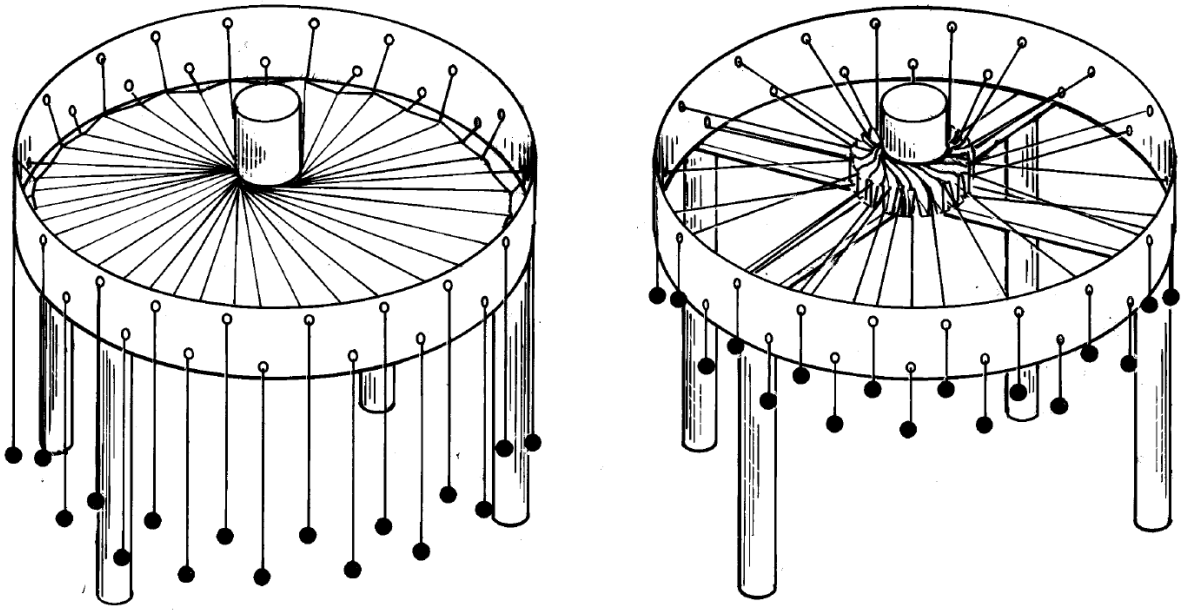

W.E. Lanford, "Folding apparatus", U.S. Patent 3010372, 1961.

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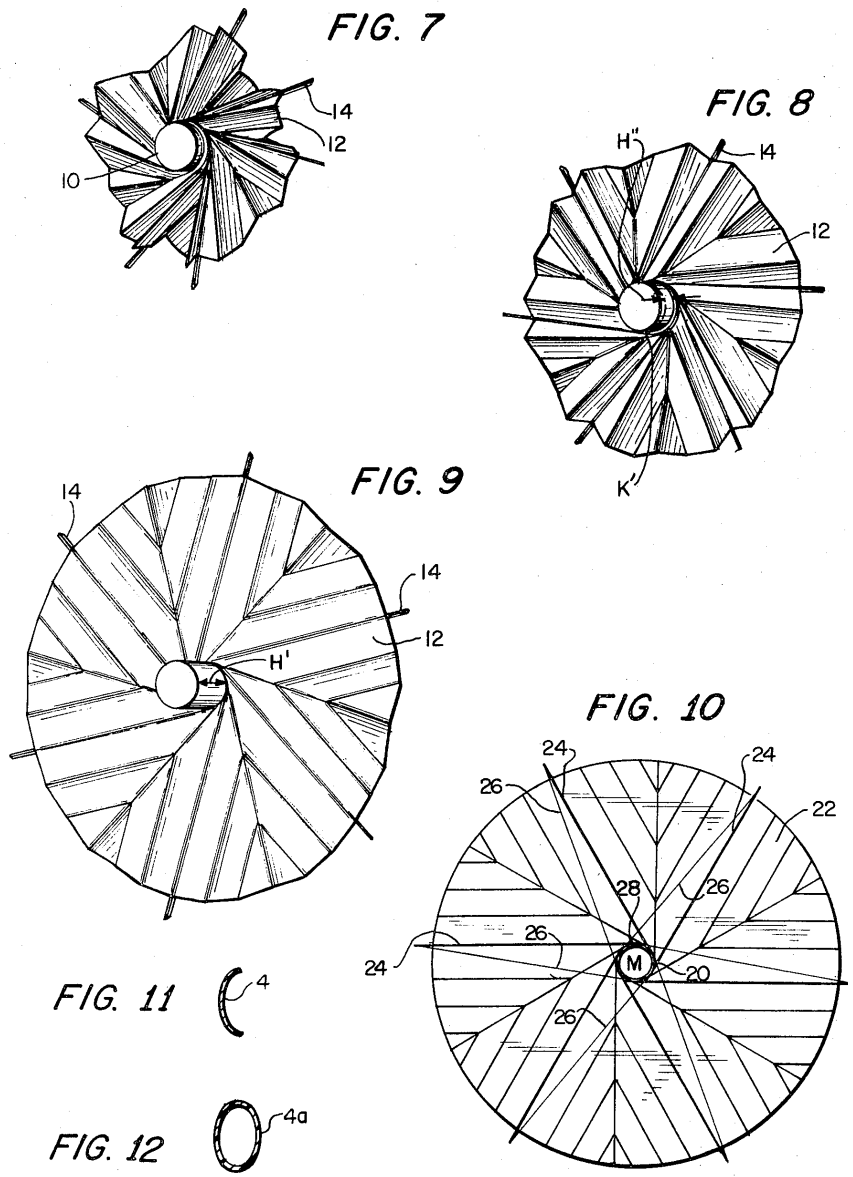

H.W. Scheel, “Space-saving storage of flexible sheets", U.S. Patent 3848821, 1974

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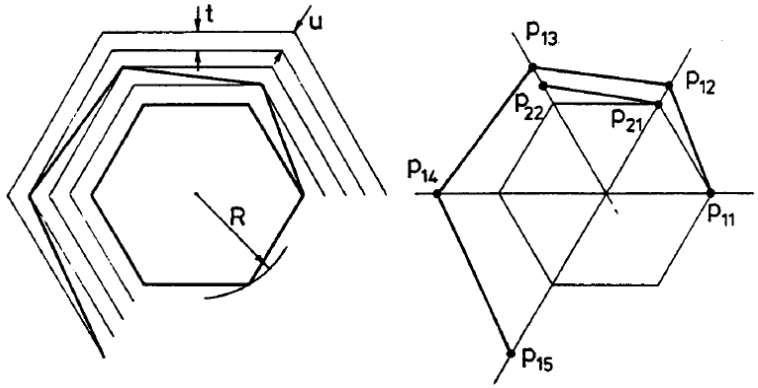

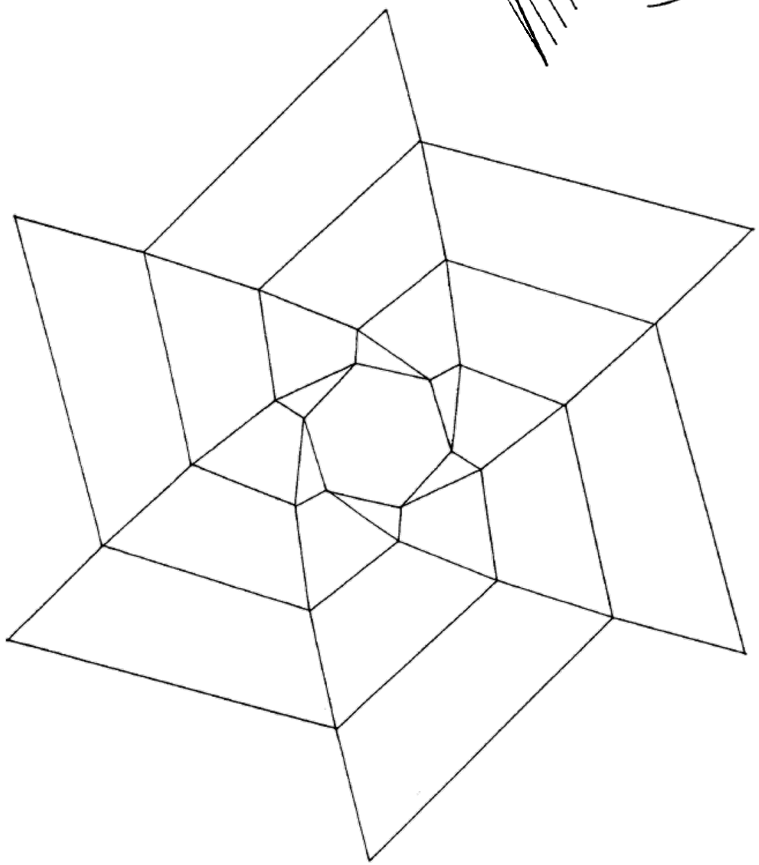

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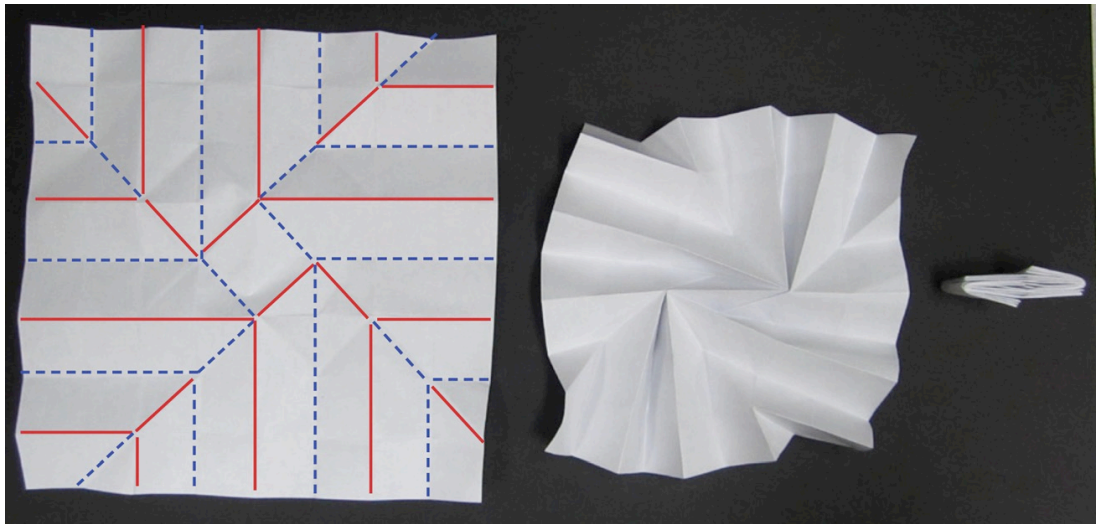

From, S. A. Zirbel *et al.*, "Accommodating Thickness in Origami-Based Deployable Arrays," *Journal of Mechanical Design*, vol. 135, no. 11, p. 111005, Oct. 2013,
based on material published in R.J. Lang, Origami in Action, St. Martin's Griffin, New York, p. 149,1997.

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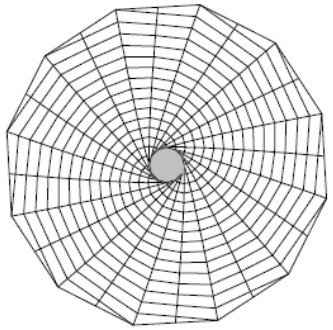
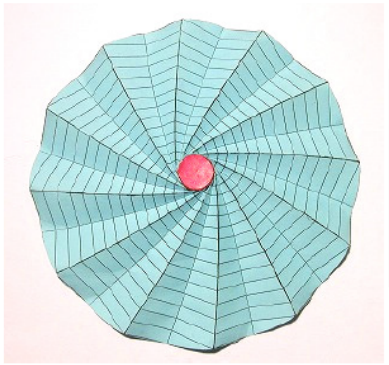


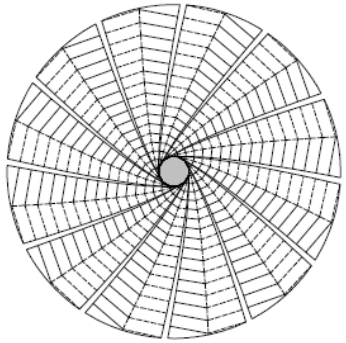
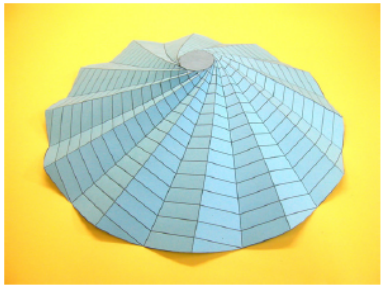
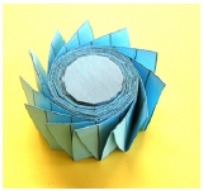
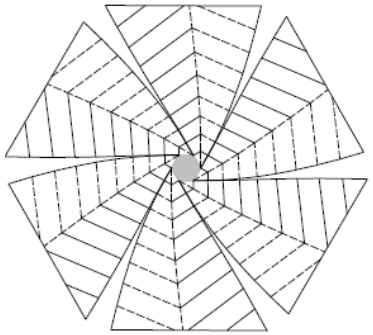
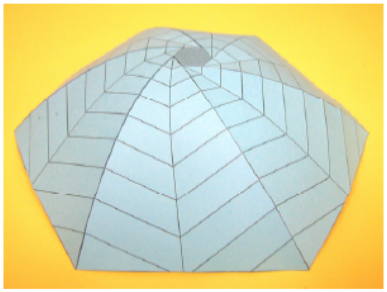
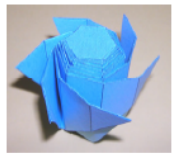

T. Nojima, "Origami Modeling of Functional Structures Based on Organic Patterns," Master's thesis, Graduate School of Kyoto University, Kyoto, Japan, 2002.

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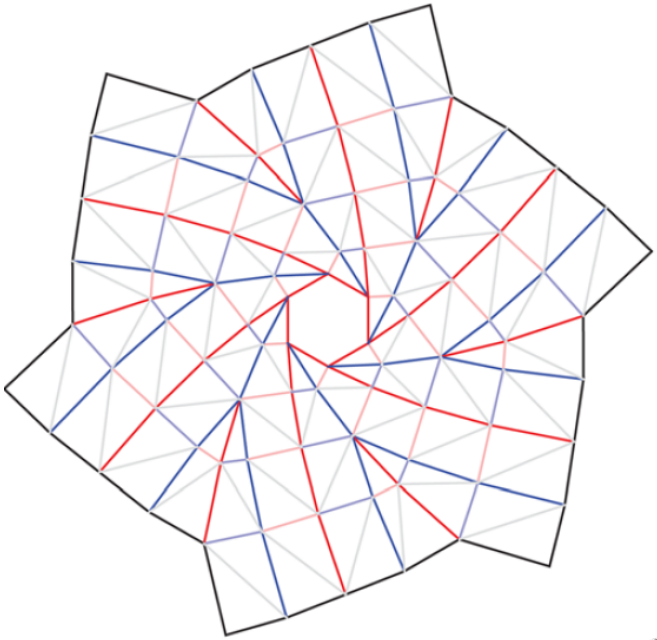

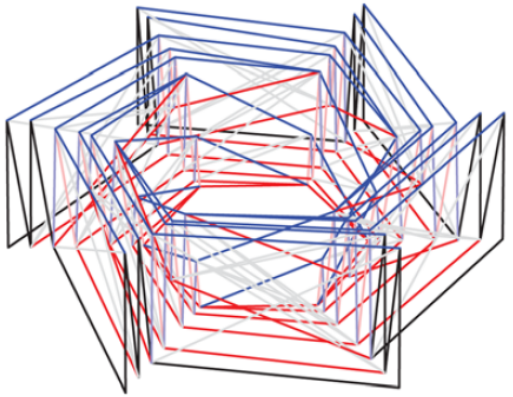

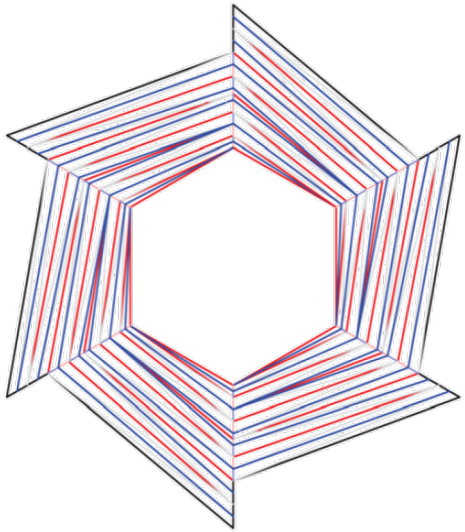

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Motivation

- Deployable solar arrays for spacecraft
  - Enable high-power solar arrays to be folded compactly for launch

https://www.nasa.gov/mission_pages/juno/news/juno20110527.html

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"Video file: NASA InSight Solar Array Deployment Test" https://www.youtube.com/watch?v=ZGsmfBgA9T4

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https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html?#id=1876

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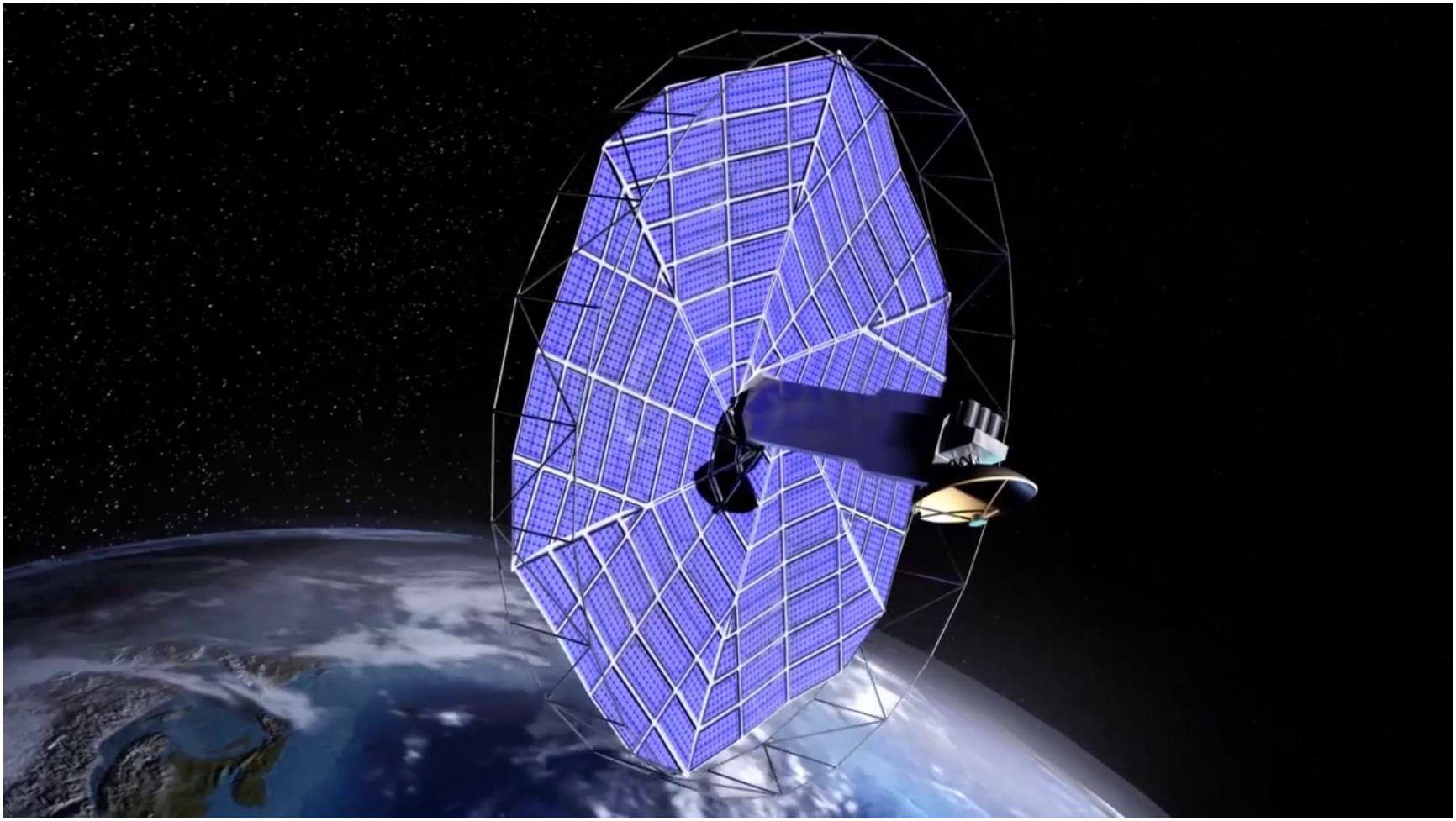

"Origami in Space: BYU-designed solar arrays inspired by origami", https://www.youtube.com/watch?v=3E12uju1vgQ

Motivation

- Deployable solar arrays for spacecraft
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- Thin, planar unfolded forms require a separate structure to provide out-of-plane stiffness
  - e.g. deployable trusses, booms, masts
- Mass, complexity, volume savings if this separate structure was not needed

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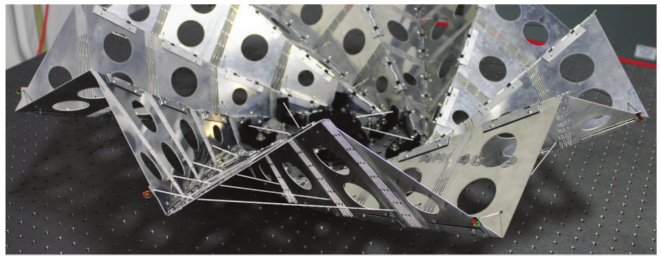

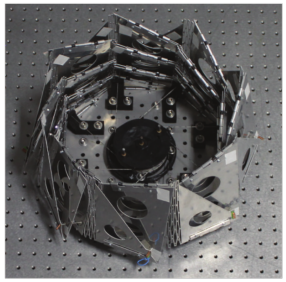

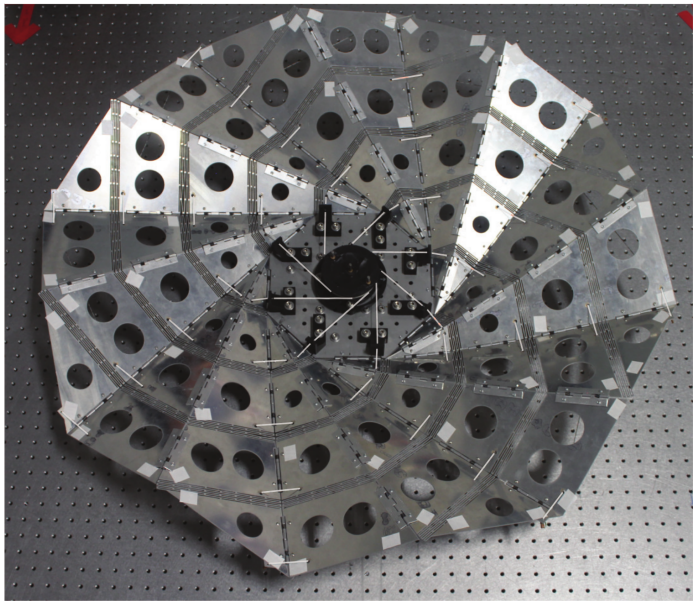

N. A. Pehrson, S. P. Smith, D. C. Ames, S. P. Magleby, and M. Arya,
"Self-Deployable, Self-Stiffening, and Retractable Origami-Based Arrays for Spacecraft," in *AIAA Scitech 2019 Forum*, San Diego, California, 2019.

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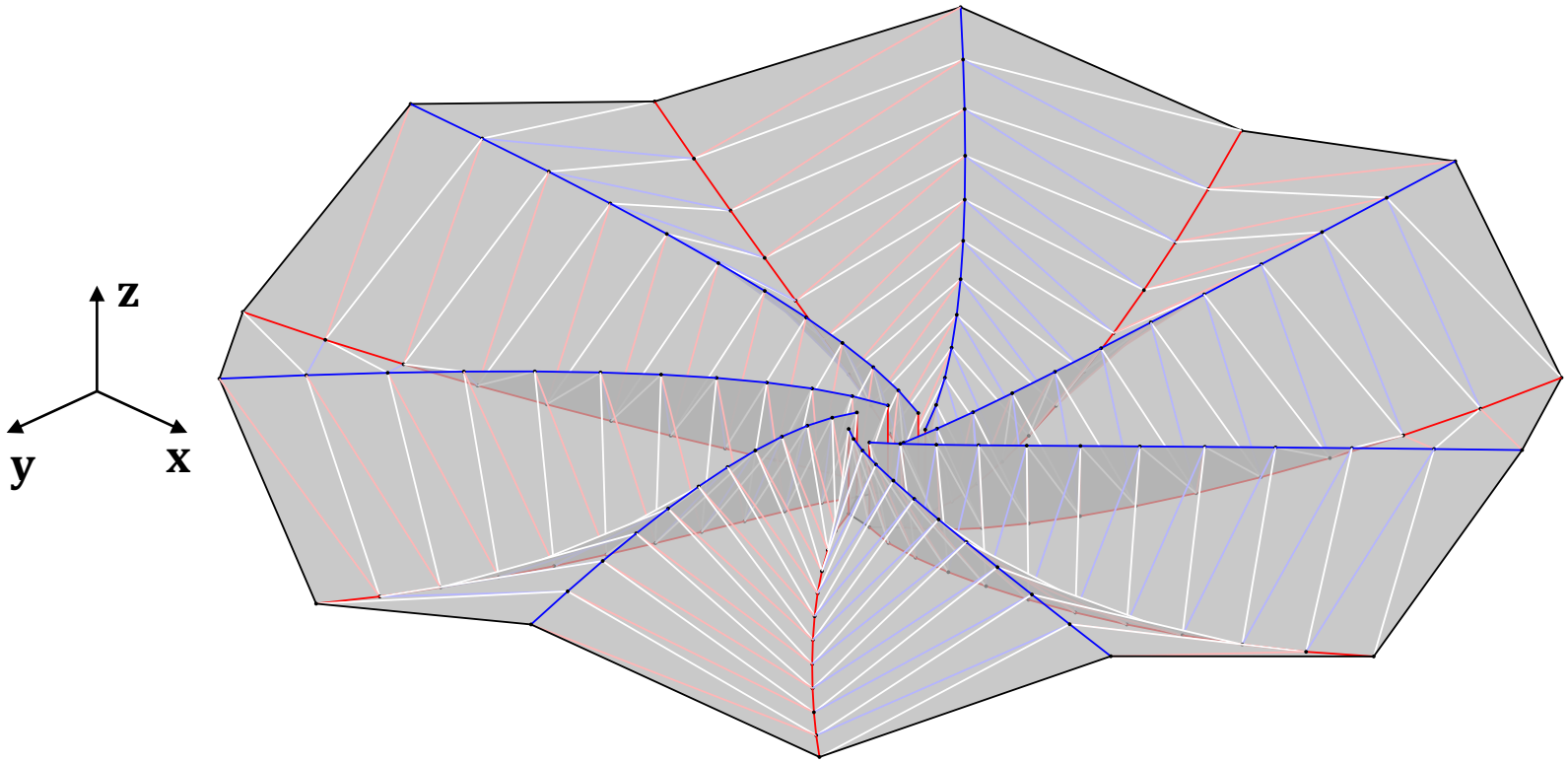
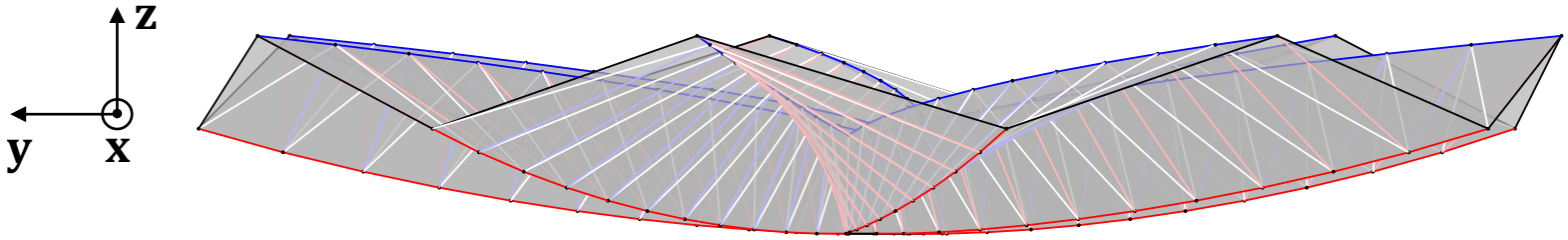
- Partially-unfolded wrapping patterns exhibit increased bending stiffness due to out-of-plane corrugations
  - Previously achieved by tension ties to prevent full unfolding
- Can an origami pattern be designed that has a non-planar corrugated form by design?

Concept overview

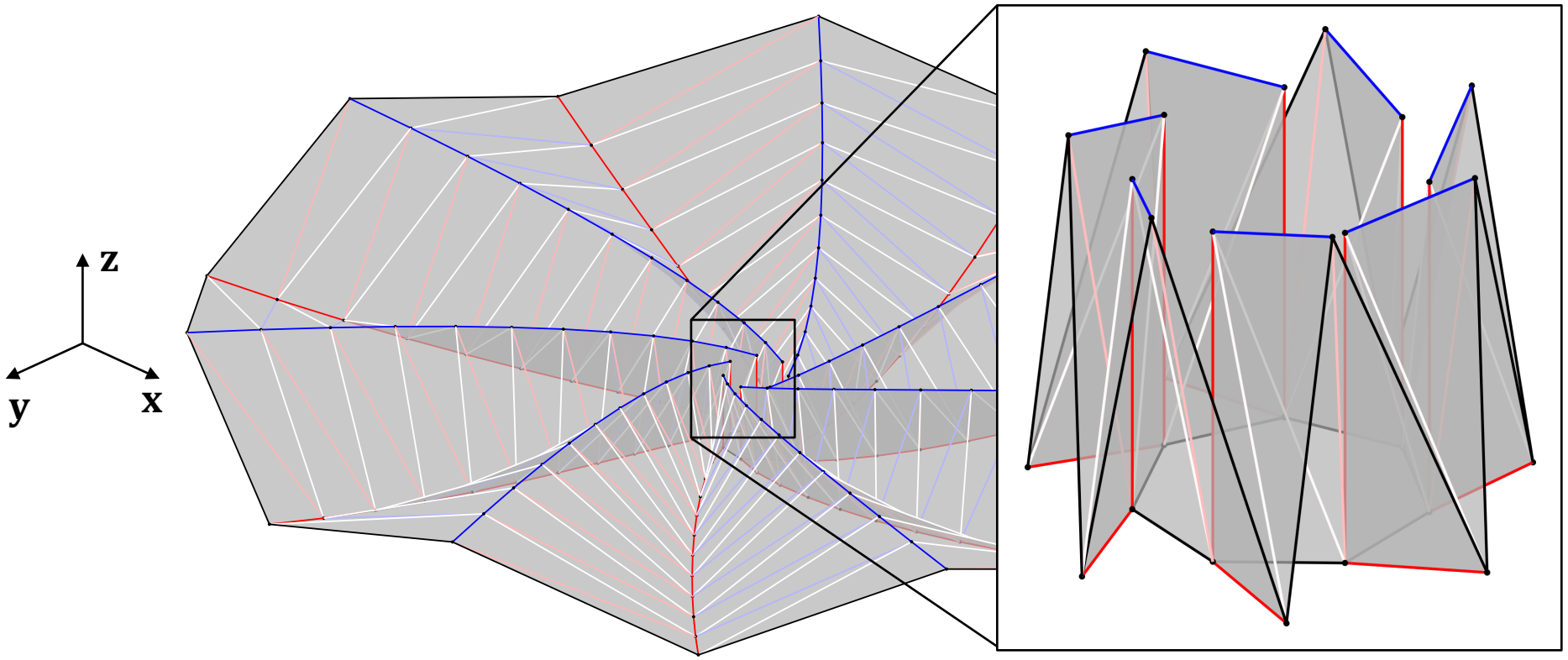


Unfolded form, isometric view



Unfolded form, side view

Concept overview



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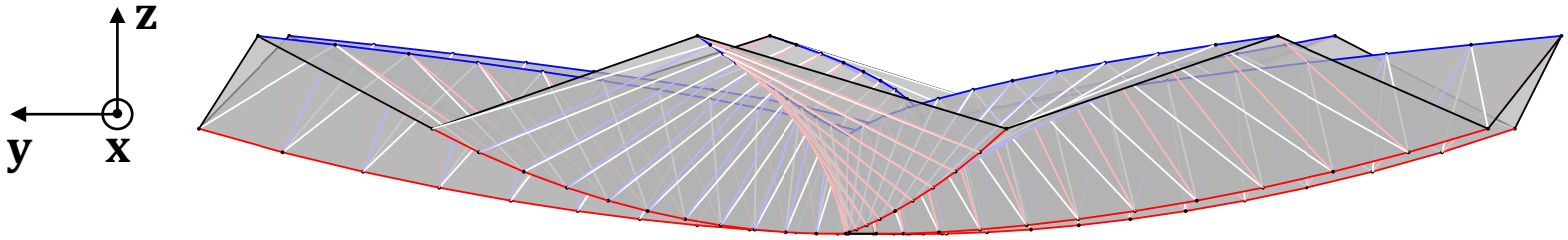

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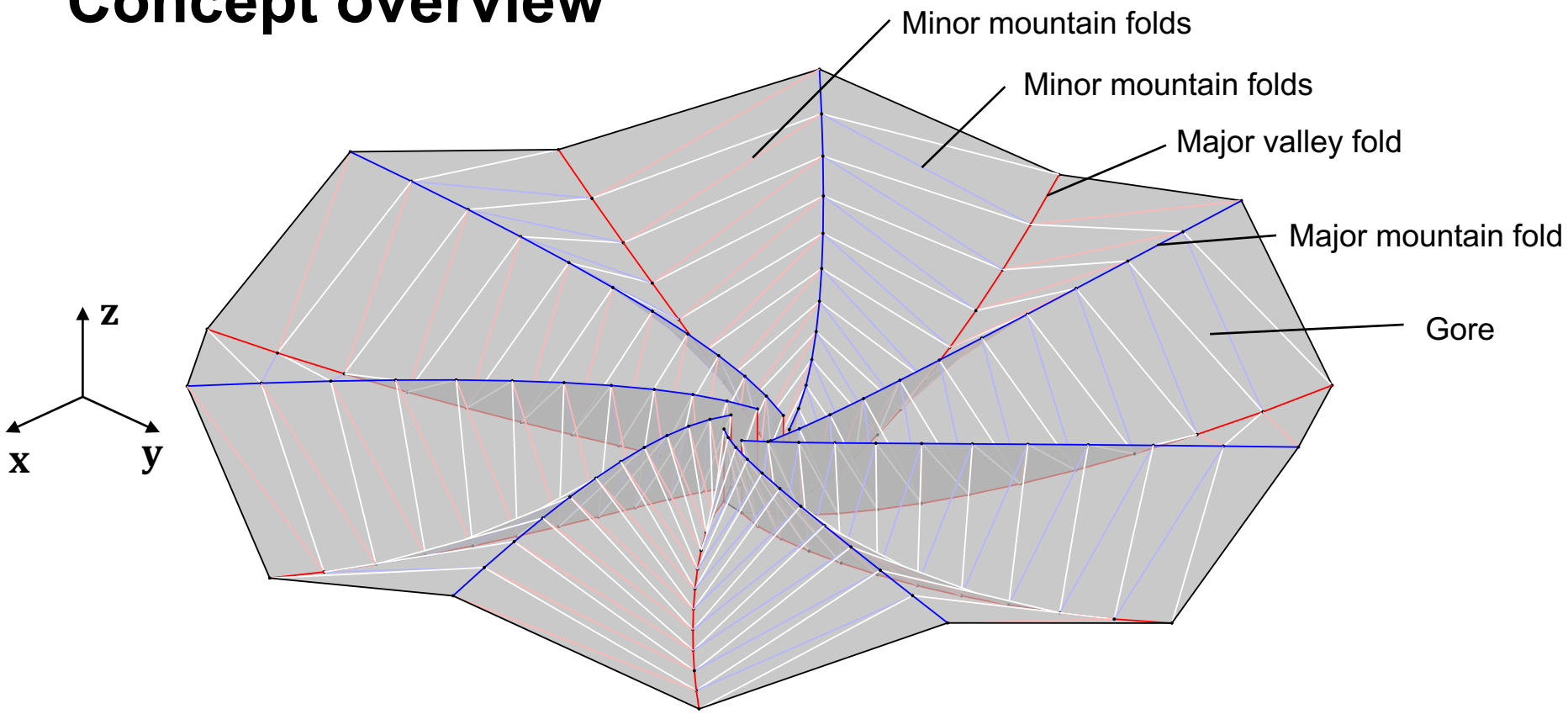

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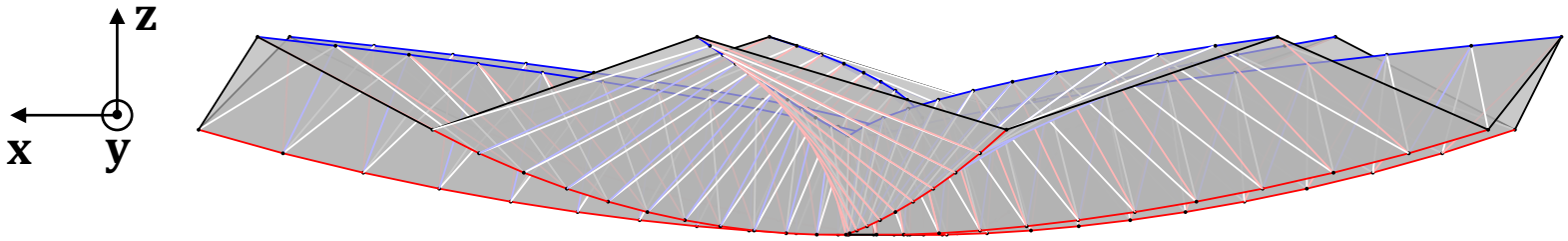

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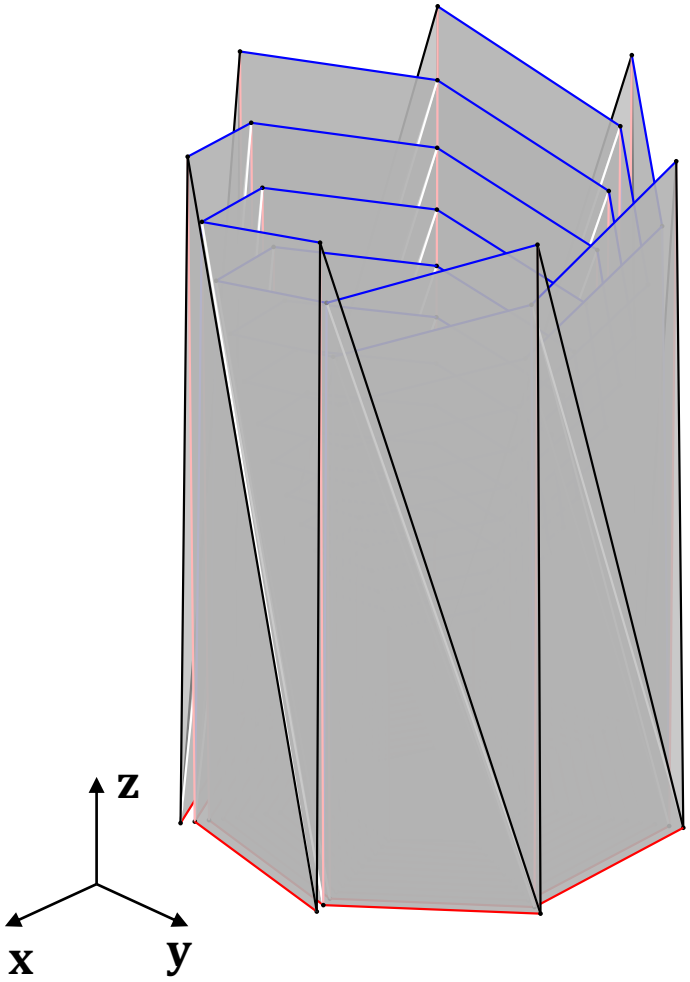

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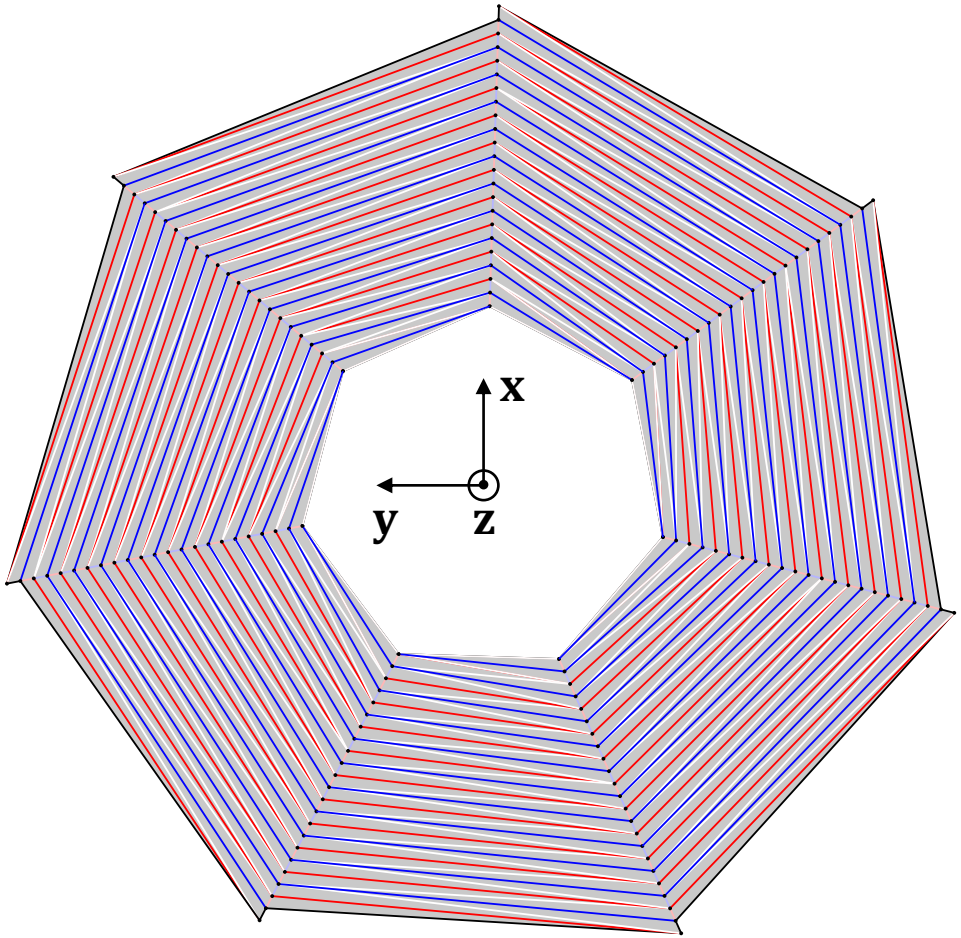

Folded form, top view

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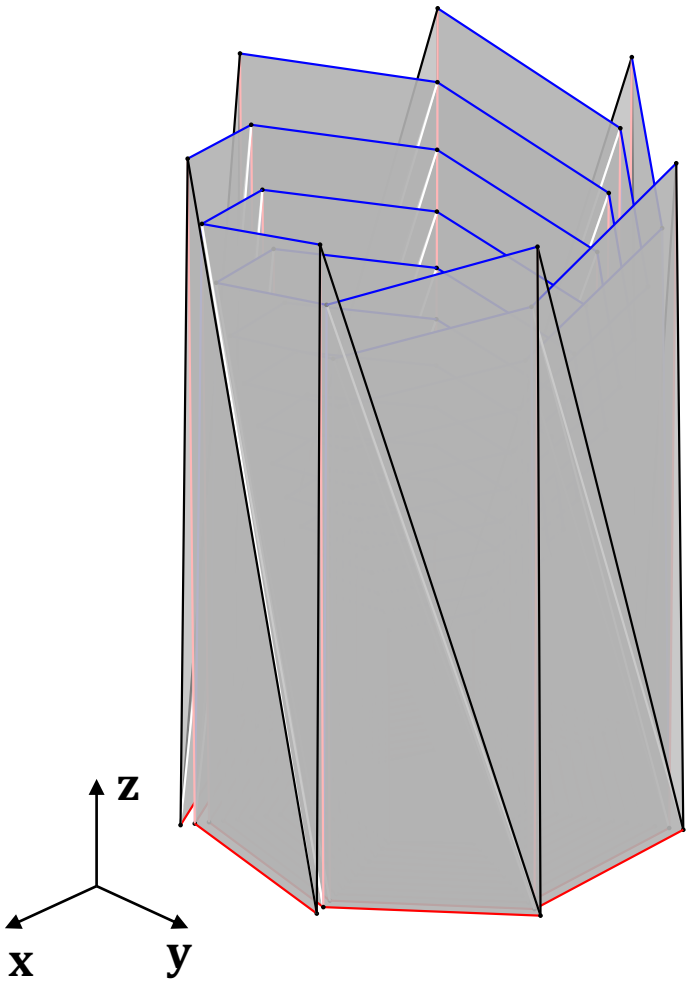
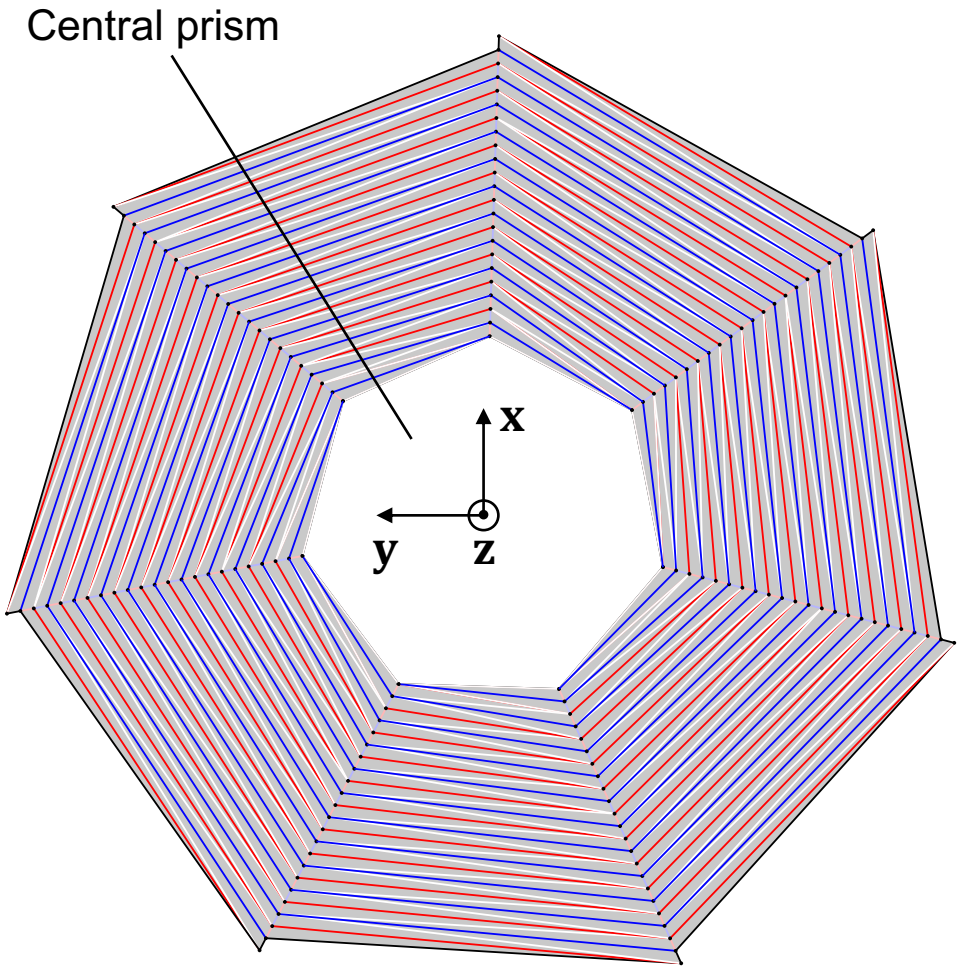


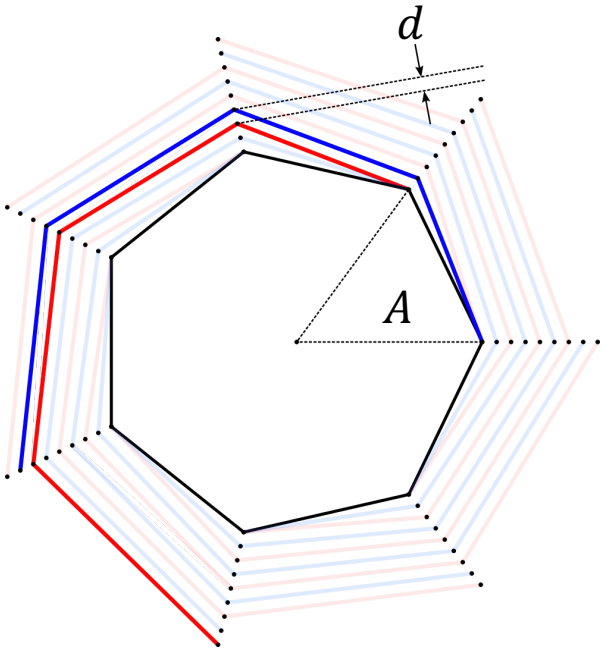
Folded form, isometric view

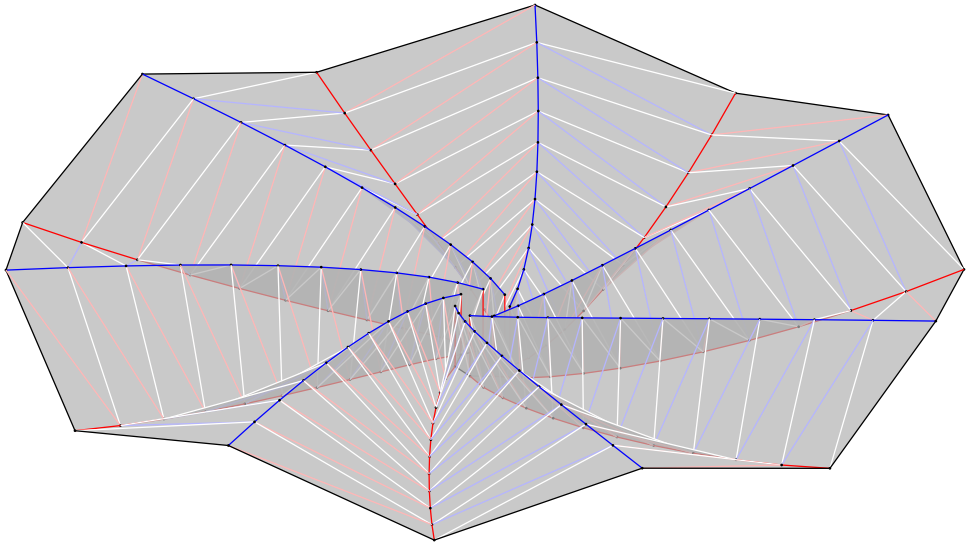


Folded form, top view

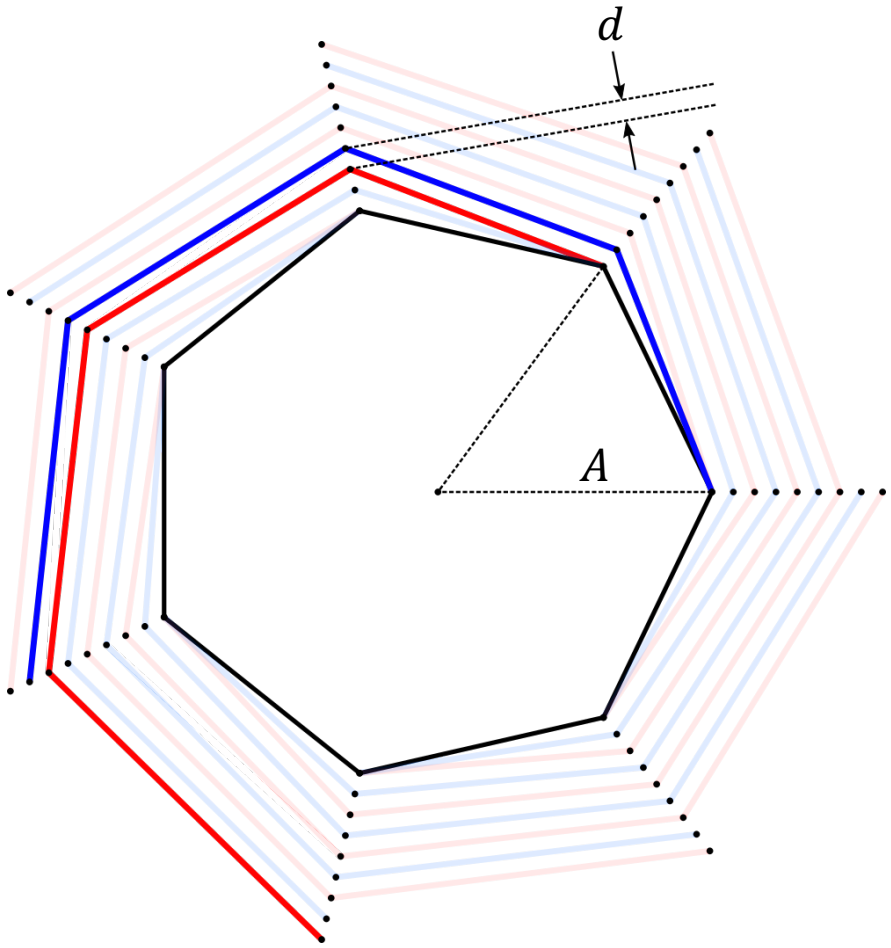
Free parameters

N	Number of sides in the central prism
n	Number of panels in a gore
A	Radius of central cylinder
d	Radial spacing between successive folded layers
z_0	Height of the first mountain node
$mz_{\text{target},\,i}$	Target heights of the unfolded mountain nodes, $i = 1, 2, \ldots n$
$vz_{\text{target},\,i}$	Target heights of the unfolded valley nodes, $i = 1, 2, \ldots n$





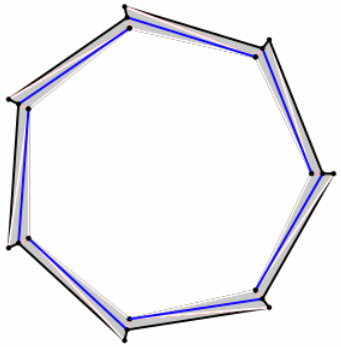
Folded form assumptions



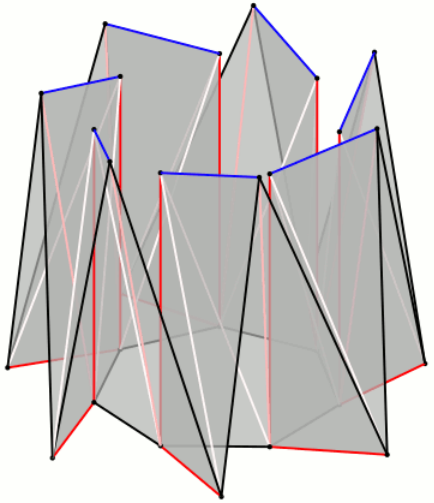
$$m_i = \boldsymbol{R}^i \begin{bmatrix} A + d(2i-1) \\ 0 \\ m_i \cdot \mathbf{z} \end{bmatrix} \qquad v_i = \boldsymbol{R}^i \begin{bmatrix} A + d(2i) \\ 0 \\ 0 \end{bmatrix}$$

Algorithm design

- Generate the fold pattern from the inside out



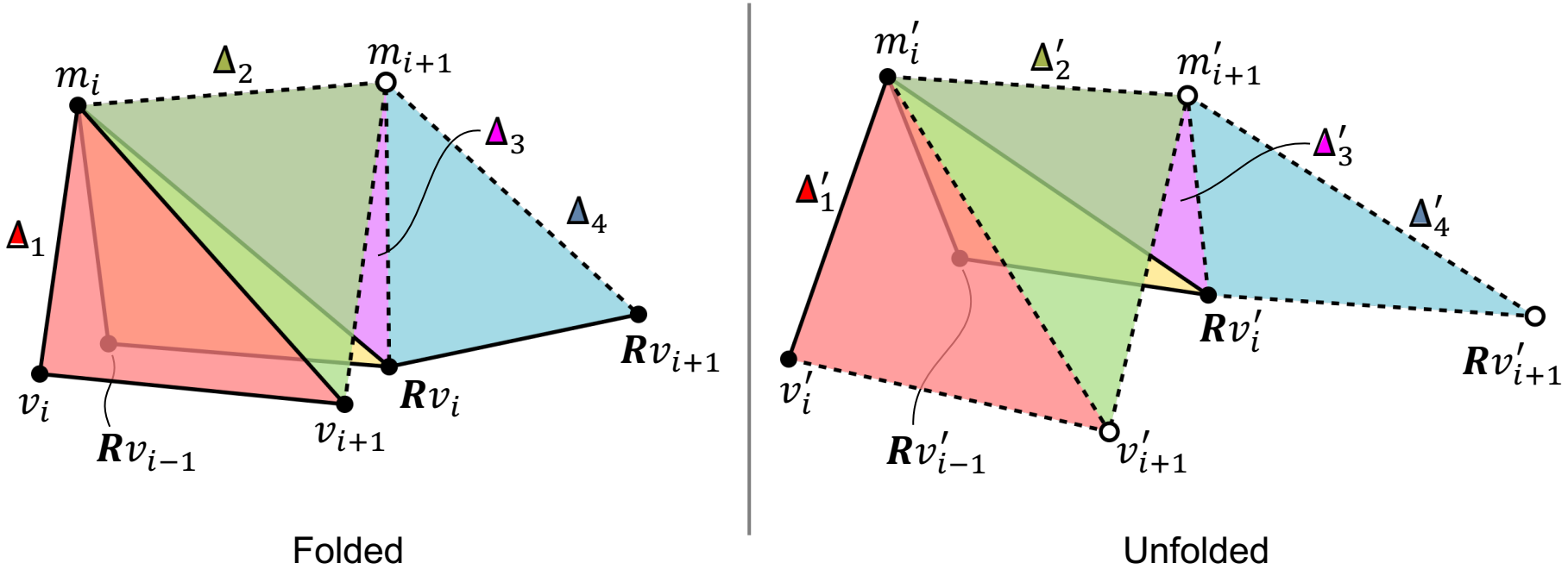
Folded



Unfolded

Algorithm design

- Assuming known m_i, v_i, find $m_{i+1}, v'_{i+1}, m'_{i+1}$



$$\text{minimize}\left(\left|m'_{i+1}\cdot\mathbf{z}-mz_{\text{target},\,i+1}\right|+\left|v'_{i+1}\cdot\mathbf{z}-vz_{\text{target},\,i+1}\right|\right)$$

over the variable $(m_{i+1}\cdot\mathbf{z})$

such that $\Delta_i = \Delta'_i$ for $i = 1, 2, 3, 4$

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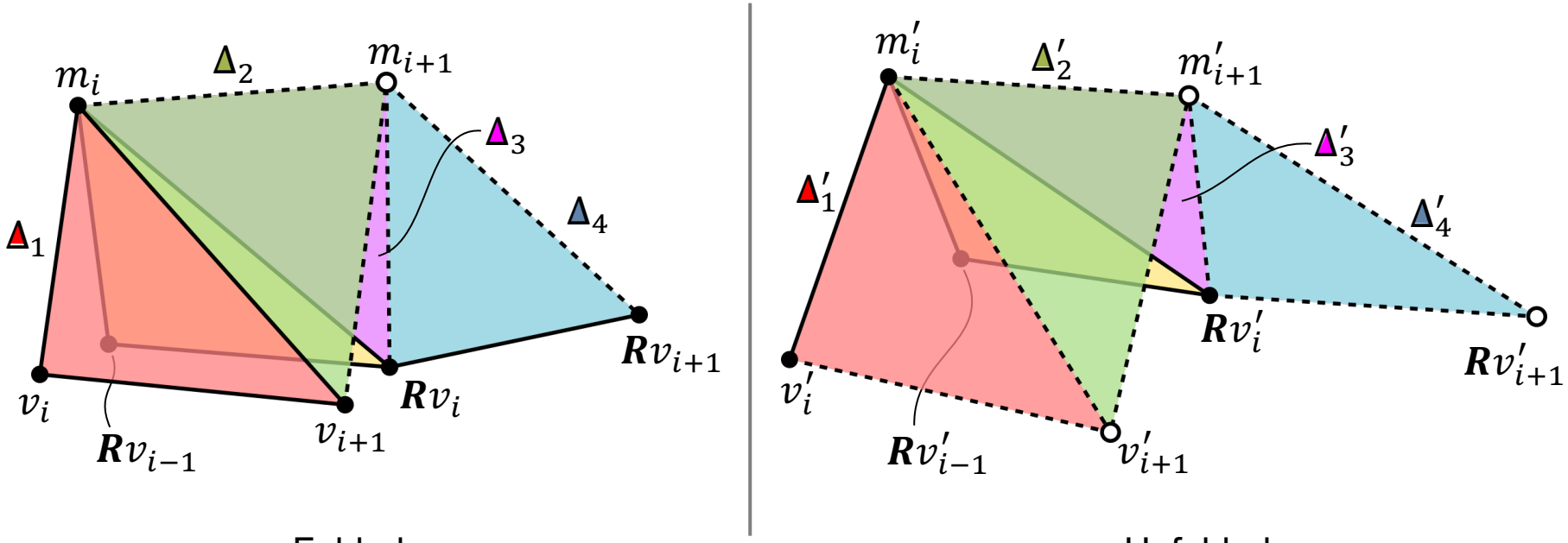
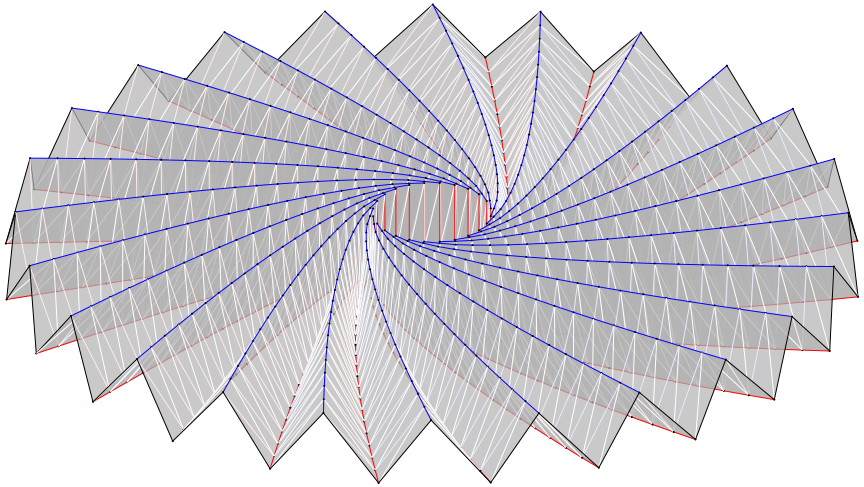


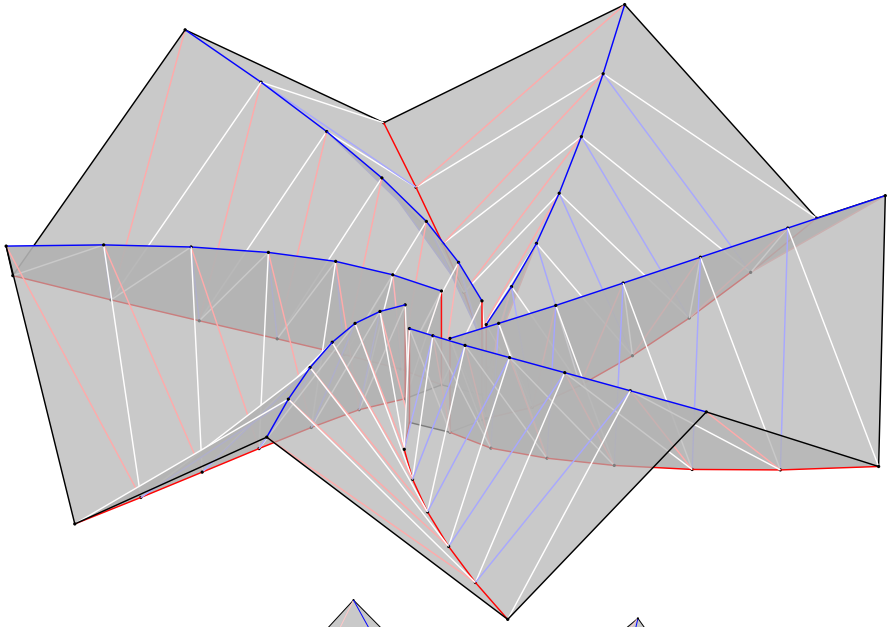
$[m'_{i+1},\ v'_{i+1}]$ = function generateFoldedPoints($m'_{i+1} \cdot \mathbf{z}$)

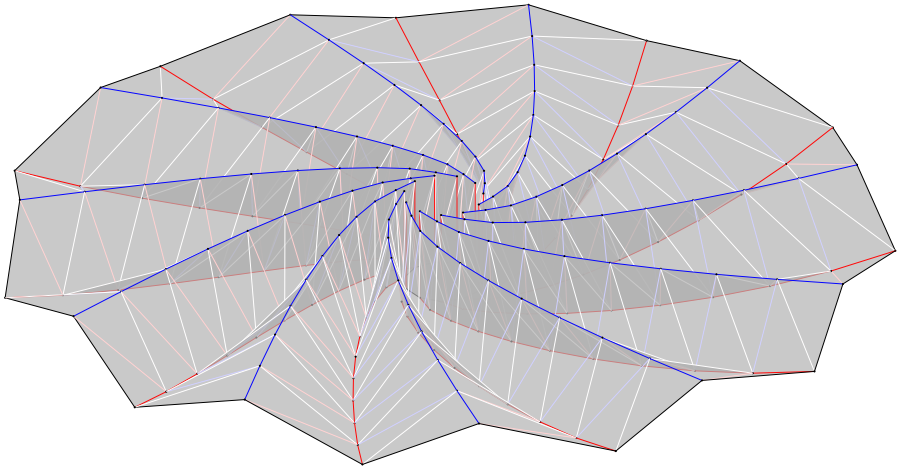
[c] = function costFunction(m'_{i+1}, v'_{i+1}, $mz_{\text{target},\,i+1}$, $vz_{\text{target},\,i+1}$)

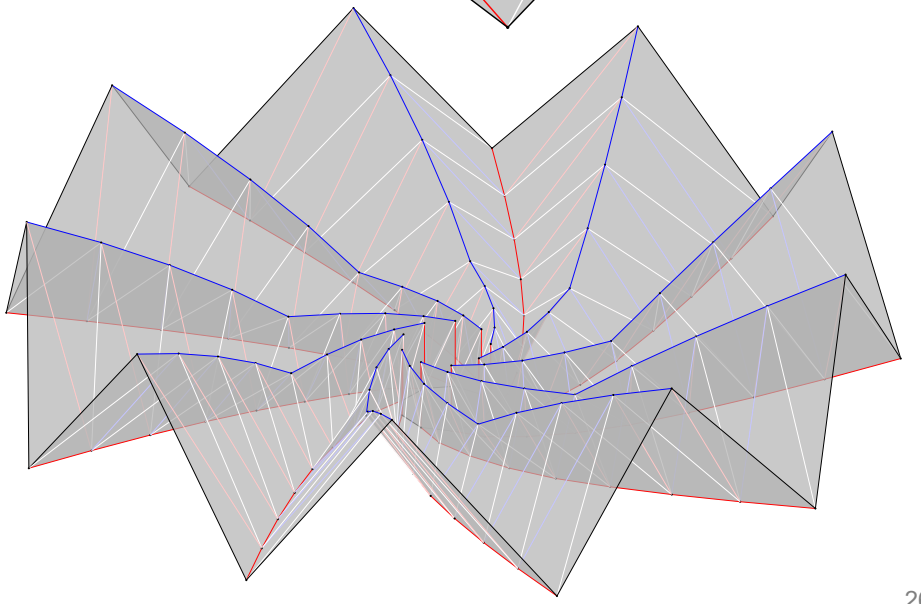
$[(m'_{i+1} \cdot \mathbf{z})^*]$ = minimize(costFunction(generatedFoldedPoints($m'_{i+1} \cdot \mathbf{z}$))

Non-planar origami wrapping zoo



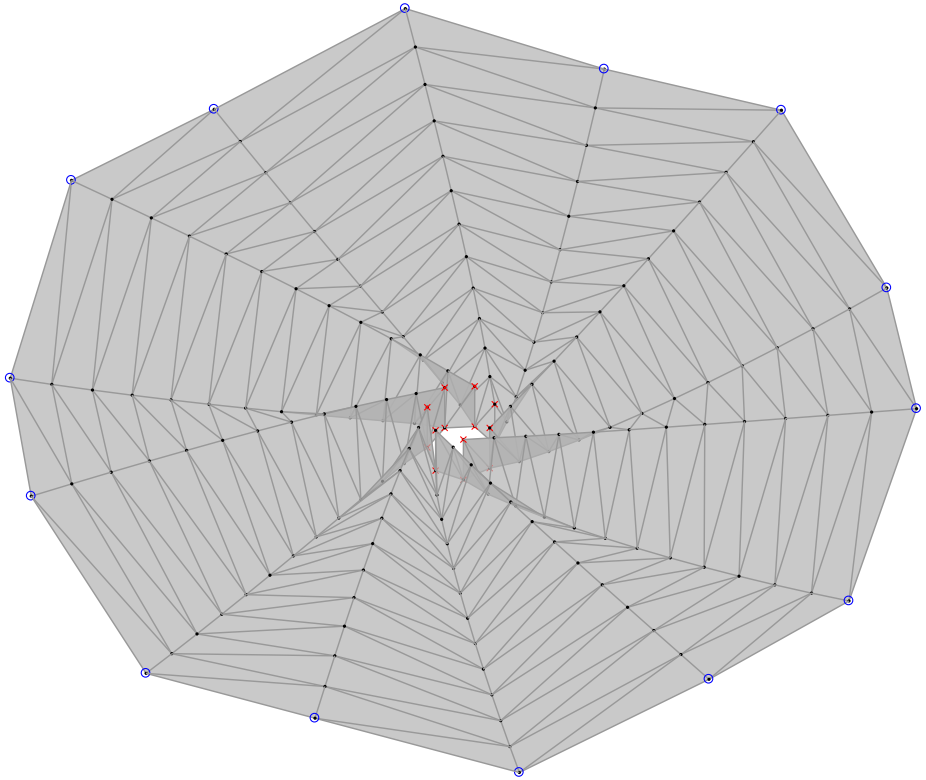






Deployed stiffness

- Innermost valley and mountain nodes are fixed
- Equal vertical loads applied to outermost valley and mountain nodes



K. Liu and G. H. Paulino, “Nonlinear mechanics of non-rigid origami: an efficient computational approach,” *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 473, 2017.
K. Liu and G. H. Paulino, “MERLIN: A MATLAB implementation to capture highly nonlinear behavior of non-rigid origami,” in *Proceedings of the IASS Annual Symposium*, Tokyo, Japan, 2016.

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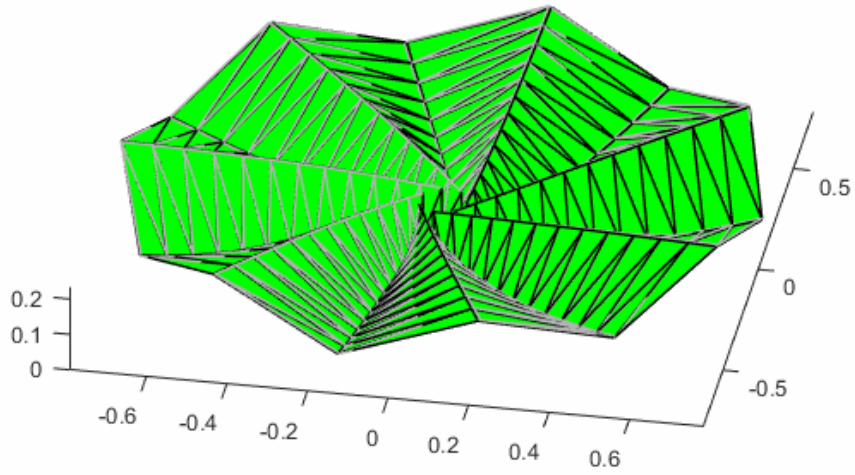
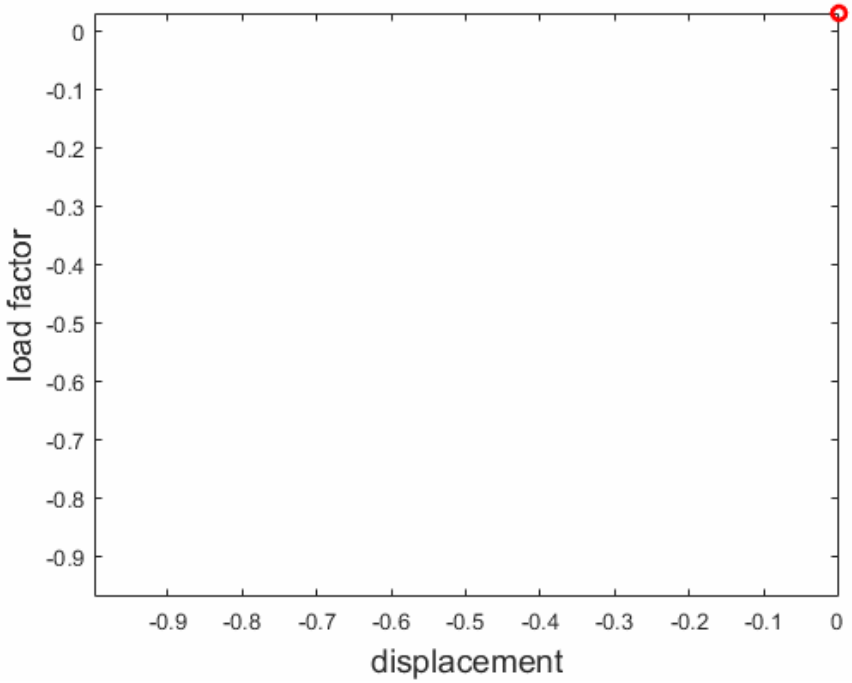
- Equal vertical loads applied to outermost valley and mountain nodes





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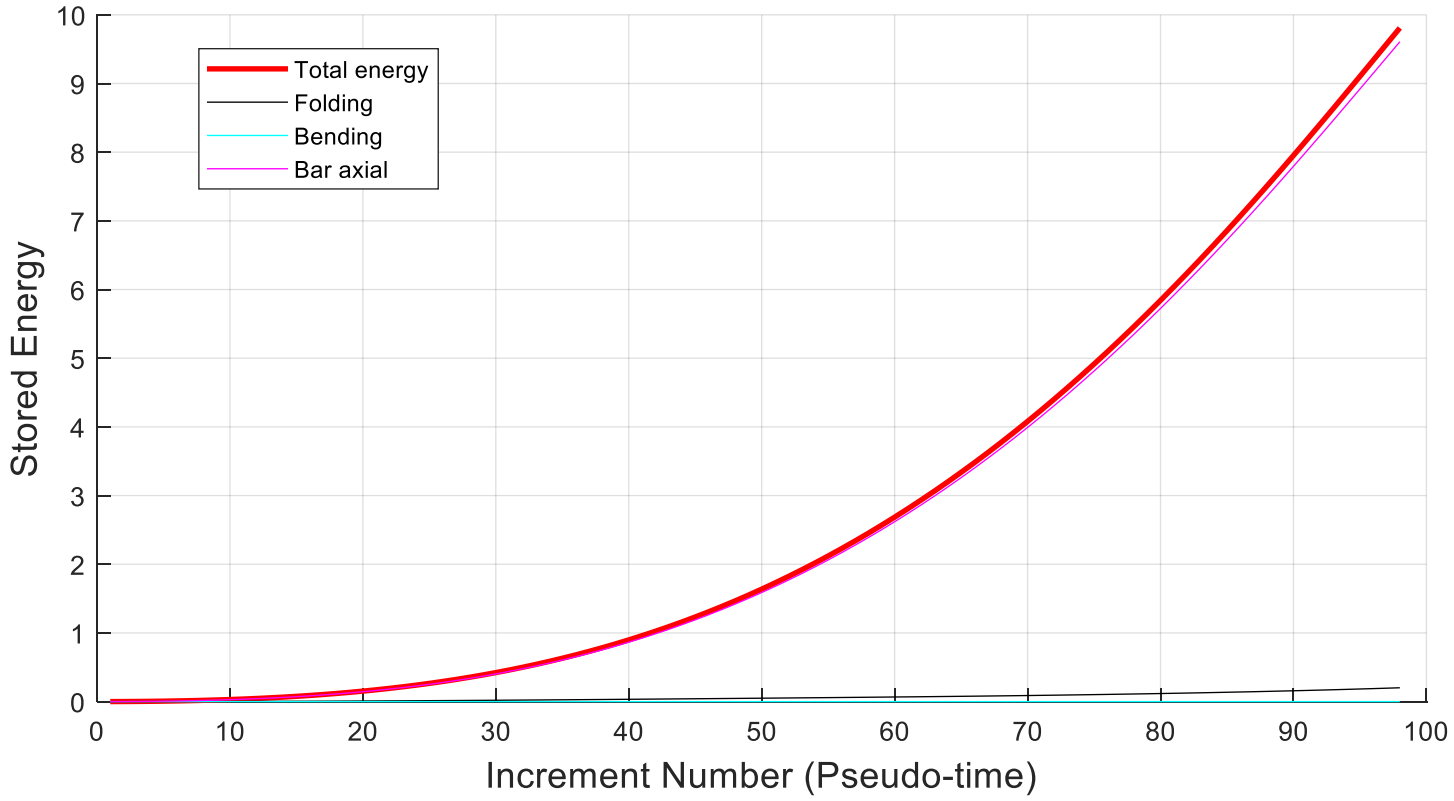
K. Liu and G. H. Paulino, "MERLIN: A MATLAB implementation to capture highly nonlinear behavior of non-rigid origami," in *Proceedings of the IASS Annual Symposium*, Tokyo, Japan, 2016.

Deployed stiffness

- Innermost valley and mountain nodes are fixed
- Equal vertical loads applied to outermost valley and mountain nodes



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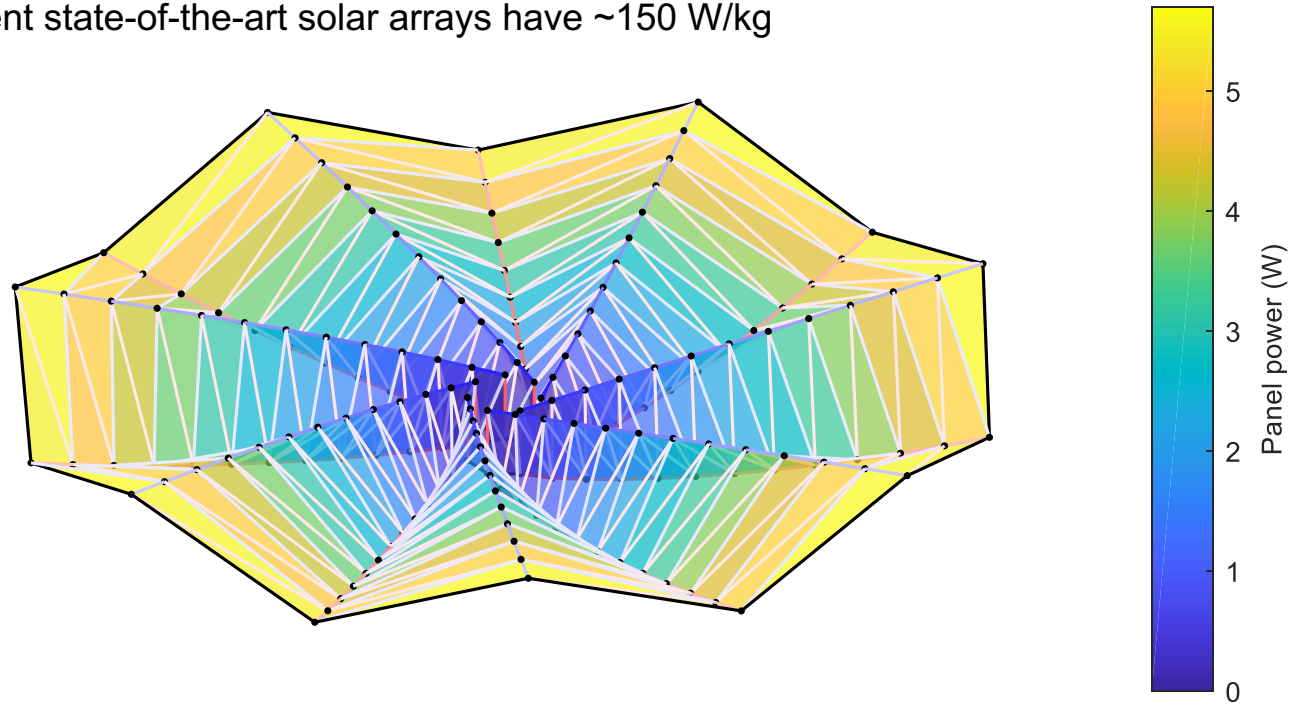
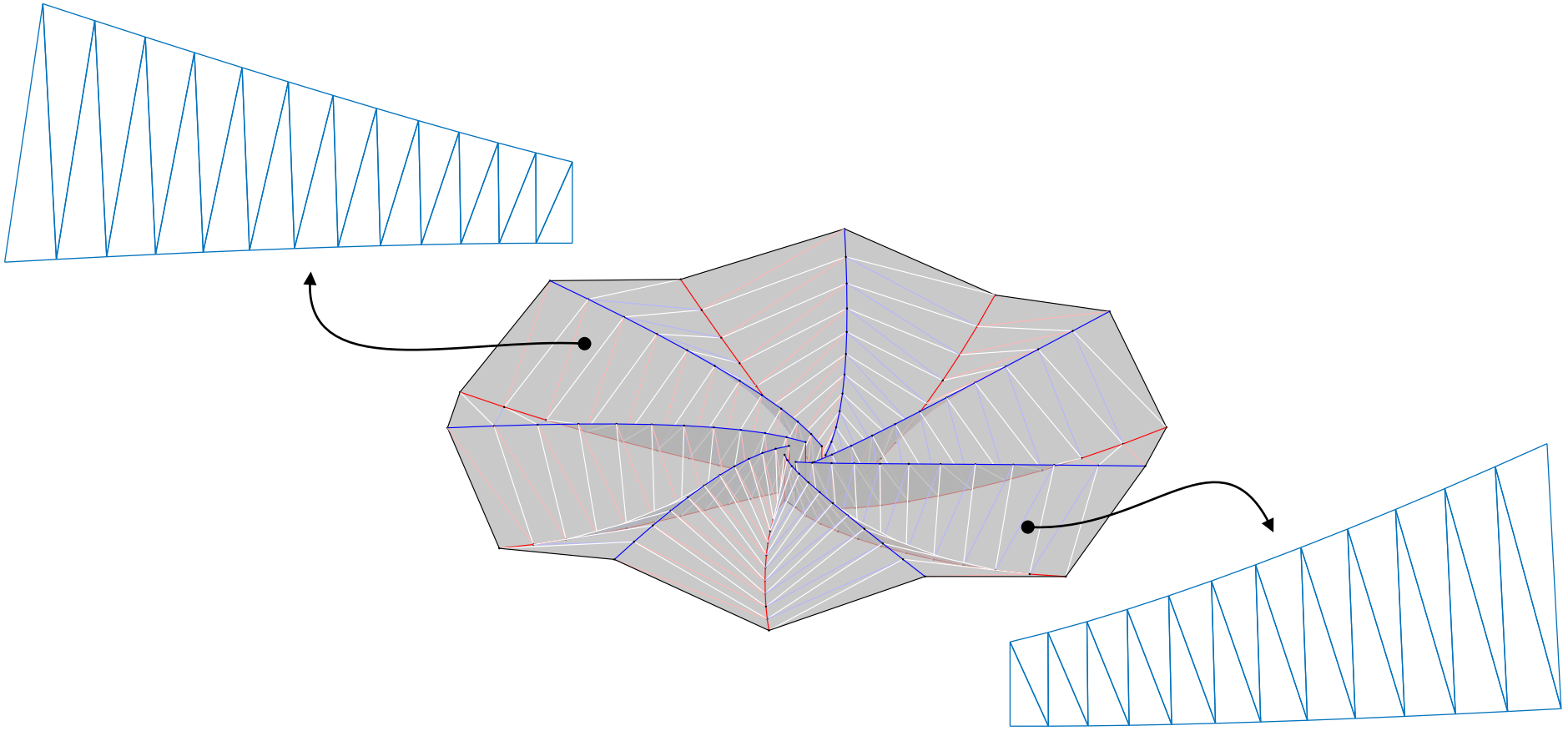
Solar array performance

- Using an example array (N = 7, unfolded diameter = 1.584m)
  - Collected power (at normal solar incidence) = 835 W
  - Power for an equivalent flat plate = 875 W
  - Corrugated surface collects 95% of the power from an equivalent flat plate
- Loss mechanisms for panels due to local angle-of-incidence effects
  - Geometric loss (cos(theta))
  - Reflective loss
- Can achieve specific power ~200 W/kg
  - Current state-of-the-art solar arrays have ~150 W/kg



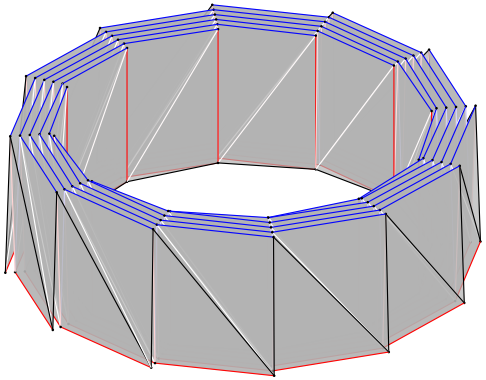
Fabrication of physical models

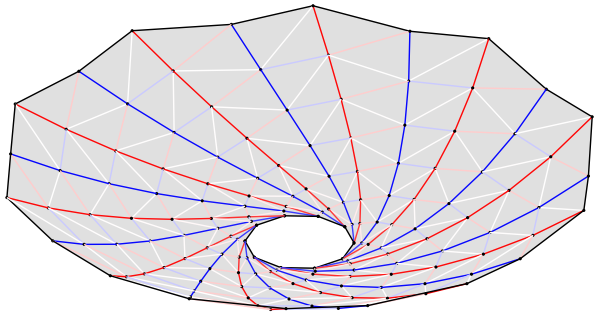
- Each gore is a chain of triangles
  - Can fabricate each gore out of planar materials

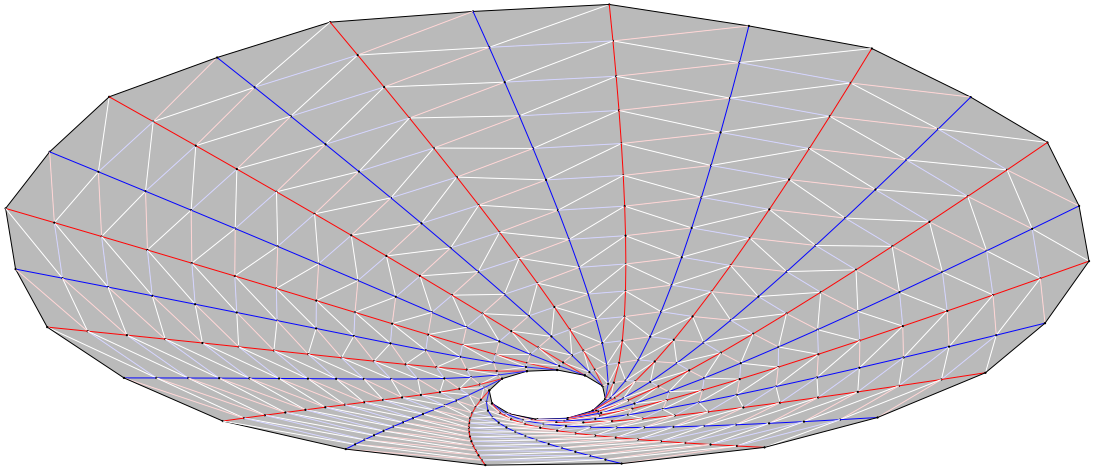


Extensions

- Can achieve different folded forms
- Can apply different objective functions to obtain different unfolded forms
  - e.g. cones, parabolas, and any other surface of revolution







Conclusions

- Developed a novel origami wrapping pattern
  - Non-planar deployed forms for out-of-plane stiffness
  - Global thickness accommodation through designed spiral folded forms
- Flexible and powerful algorithm to generate target folded forms, or target unfolded forms
- Can be simply fabricated using planar materials
- Applicable to novel lightweight deployable solar array (200 W/kg, or 30% improvement over state-of-the-art)

Acknowledgments

- Dr. Jonathan Grandidier assisted with the calculation of solar array power output.
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Concept Overview